

University of Montana

## ScholarWorks at University of Montana

---

Graduate Student Theses, Dissertations, &  
Professional Papers

Graduate School

---

2001

### Simulating the effects of climate change on the carbon balance of North American high latitude forests

Alisa Renae Keyser  
*The University of Montana*

Follow this and additional works at: <https://scholarworks.umt.edu/etd>

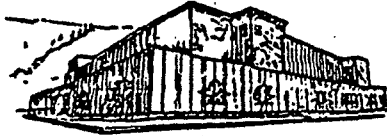
**Let us know how access to this document benefits you.**

---

#### Recommended Citation

Keyser, Alisa Renae, "Simulating the effects of climate change on the carbon balance of North American high latitude forests" (2001). *Graduate Student Theses, Dissertations, & Professional Papers*. 5674.  
<https://scholarworks.umt.edu/etd/5674>

This Thesis is brought to you for free and open access by the Graduate School at ScholarWorks at University of Montana. It has been accepted for inclusion in Graduate Student Theses, Dissertations, & Professional Papers by an authorized administrator of ScholarWorks at University of Montana. For more information, please contact [scholarworks@mso.umt.edu](mailto:scholarworks@mso.umt.edu).



**Maureen and Mike  
MANSFIELD LIBRARY**

The University of

**Montana**

---

Permission is granted by the author to reproduce this material in its entirety,  
provided that this material is used for scholarly purposes and is properly cited in  
published works and reports.

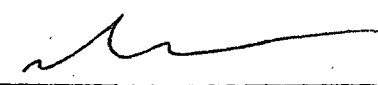
**\*\*Please check "Yes" or "No" and provide signature\*\***

Yes, I grant permission

yes

No, I do not grant permission

\_\_\_\_\_

Author's Signature: 

Date: '13 September 2001

Any copying for commercial purposes or financial gain may be undertaken only with  
the author's explicit consent.

---

# **Simulating the effects of climate change on the carbon balance of North American high latitude forests**

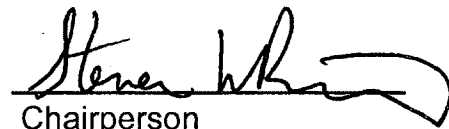
by

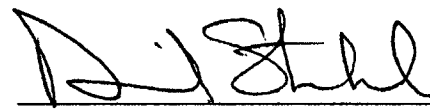
Alisa Renae Keyser

B.A. Boston University

presented in partial fulfillment of the requirements  
for the degree of  
Master of Science  
The University of Montana  
2001

Approved by :

  
Chairperson

  
Dean of Graduate School

10 SEPTEMBER 2001

Date

UMI Number: EP41138

All rights reserved

INFORMATION TO ALL USERS

The quality of this reproduction is dependent upon the quality of the copy submitted.

In the unlikely event that the author did not send a complete manuscript and there are missing pages, these will be noted. Also, if material had to be removed, a note will indicate the deletion.

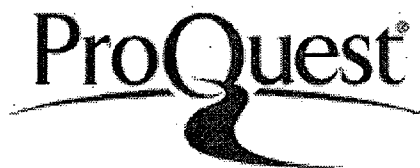


UMI EP41138

Published by ProQuest LLC (2014). Copyright in the Dissertation held by the Author.

Microform Edition © ProQuest LLC.

All rights reserved. This work is protected against unauthorized copying under Title 17, United States Code



ProQuest LLC.  
789 East Eisenhower Parkway  
P.O. Box 1346  
Ann Arbor, MI 48106 - 1346

Simulating the effects of climate change...

Director: Steven W. Running



The large magnitude of predicted warming at high latitudes and the potential feedback of ecosystems to atmospheric CO<sub>2</sub> concentrations make it important to quantify both warming and its effects on high latitude carbon balance. We analysed long-term, daily surface meteorological records for thirteen sites in Alaska and northwestern Canada and an 82 year record of river ice breakup date for the Tanana River in interior Alaska. We found increases in winter and spring temperature extrema for all sites, with the greatest increases in spring minimum temperature, average 0.47 °C/10yrs, and a 0.7 day/10yrs advance in ice breakup on the Tanana River. We used the climate records to drive an ecosystem process model, BIOME\_BGC, to simulate the effects of climate change on the carbon and water balances of boreal forest ecosystems. The growing season has lengthened an average of 2.6 days/10yrs with an advance in average leaf onset date of 1.10 days/10yrs. This advance in the start of the active growing season correlates positively to progressively earlier ice breakup on the Tanana River in interior Alaska. The advance in the start of the growing season resulted in a 20% increase in net primary production for both aspen (*Populus tremuloides*) and white spruce (*Picea glauca*) stands. Aspen had a greater mean increase in maintenance respiration than spruce, whereas spruce had a greater mean increase in evapotranspiration. Average decomposition rates also increased for both species. Both net primary production and decomposition are enhanced in our simulations, suggesting that productive forest types may not experience a significant shift in net carbon flux as a result of climate warming.

## **Acknowledgements**

It has been quite an unscheduled stop for me here at NTSG, in what I must say was initially quite foreign terrain. I am incredibly thankful to everyone who helped me to navigate the landscape, especially to Ramakrishna Nemani and Michael White at the outset. I am thankful to Dr. Steve Running for taking me on as a student under untraditional circumstances; I learned and experienced more than I could have imagined. I thank Rama for support, advice, and extended discussions in which so much science and life was covered, and especially for all the curry. Saxon Holbrook deserves great thanks for his help and patience in handling the many computer problems that I both invented and suffered from. I thank my committee for being especially flexible, supportive, and wise during the unusual course of this work. All of the members of NTSG, both past and present, have provided an enriching, talented, and down right fun place to learn and work. Lastly, I thank my family for the unending support and encouragement in all that I undertake.

<b>Table of Contents</b>	<b>page</b>
Title Page	
Abstract . . . . .	ii
Acknowledgements . . . . .	iii
Table of Contents . . . . .	iv
List of Tables. . . . .	v
List of Figures. . . . .	vi
Introduction . . . . .	1
Methods . . . . .	4
Climate Analysis . . . . .	4
Growing Season Length . . . . .	5
Simulated Carbon Balance. . . . .	6
Results and Discussion . . . . .	8
Climate Analysis . . . . .	8
Growing Season Length . . . . .	10
Simulated Carbon Balance. . . . .	11
Conclusions . . . . .	16
References . . . . .	18
Tables . . . . .	22
Figures . . . . .	27

## List of Tables

Table 1 (page 22).

Station Descriptions. Meteorological station location coordinates, elevation, first year of record (all records end in 1997), and annual average temperature statistics (long-term means and trends).

Table 2 (page 23).

BIOME-BGC physiological and soil parameters for simulation runs.

Table 3a (page 24).

Summary of trends in seasonal values for maximum daily temperature. Changes and SEs are given per decade ( $^{\circ}\text{C}$  per 10y).

Table 3b (page 25).

Summary of trends in seasonal values for minimum daily temperature. Changes and SEs are given per decade ( $^{\circ}\text{C}$  per 10y).

Table 4 (page 26).

Summary of trends in growing season length ( $\pm 1\text{SE}$ ), yearday leaf offset minus yearday leaf onset, as defined by the phenology sub-model of BIOME-BGC.



## List of Figures

### Figure 1 (page 27).

Trend in spring average temperature anomaly compared to trend in Tanana River ice breakup date for interior Alaska. For the period of overlap, 1949-1997, the yearday of river breakup is inversely correlated to spring average temperature with a slope of  $-1.76 \pm 0.20$  ( $r^2 = 0.45$ ,  $p < 0.0001$ ). **a)** Spring average temperature anomaly for interior Alaska stations for the period 1949-1997. We averaged the deviation from long-term mean average spring temperature, March through May, for Bettles Field, Fairbanks, and Big Delta in each year and performed a linear regression on the averaged anomaly series. **b)** Julian yearday of Tanana River ice breakup at Nenana, AK (ca. 40km from Fairbanks) from 1917-1998 plotted with regression line.

### Figure 2 (page 28).

Average change in yearday of leaf onset in spring for deciduous canopies computed by the phenology submodel of BIOME\_BGC (White *et al.* 1997). Leaf onset is represented as the deviation, in days, from the long-term mean for each site and averaged for all sites. The bulk of the trend in leaf onset is due to advances in onset in Alaska of 3days/10yrs. **a)** Average change for thirteen sites in Alaska and Canada. **b)** Alaska sites. **c)** Canada sites.

### Figure 3 (page 29-32).

Annual average temperature (TAVE) from meteorological station records, and annual ET and NPP as simulated from BIOME\_BGC for the coldest and warmest of the interior sites and two biome types. Bettles Field is the coldest interior site with an annual average temperature =  $-5.5^{\circ}\text{C}$ ; Fort McMurray is the warmest interior site with an annual average temperature =  $0.15^{\circ}\text{C}$ . **a)** Aspen at Bettles Field, AK. **b)** Aspen at Fort McMurray. **c)** White spruce at Bettles Field. **d)** White spruce at Fort McMurray.

### Figure 4 (page 33).

Changes in simulated decomposition rate scalar (DRS) for two sites and biome types. The decomposition rate scalar is a unit-less number (dim) and is a function of soil water availability and soil temperature. **a)** Aspen at Bettles Field, AK. **b)** Aspen at Fort McMurray. **c)** White spruce at Bettles Field. **d)** White spruce at Fort McMurray.

## Introduction

Boreal forests cover ca. 11% of the Earth's land surface and contain ca. 16-24% of global soil carbon (Gates 1993; Bonan *et al.* 1992b; Bonan *et al.* 1989). At high latitudes, extreme seasonality, cold temperatures, permafrost, and a short growing season result in low rates of primary productivity and slow decomposition of organic matter. Given the large stores of carbon in both the living biomass and soil, the response of these ecosystems to a warming climate may initiate substantial feedbacks to atmospheric CO<sub>2</sub> concentrations. Increases in net primary production will result in increased carbon storage and a negative feedback; increases in the rate of organic matter decomposition will release carbon to the atmosphere in a positive feedback.

Global circulation models indicate that warming will be greatest at high latitudes and that this increase will be most pronounced in winter and spring months (IPCC 1995). Chapman *et al.* (1993) showed an increase in sea surface temperatures from 1961-1990 in the high latitudes that is most pronounced in the winter and spring and a decrease in summer ice extent over the arctic. For the period 1973-1992, increases in spring temperature correlate with a 10% decrease in North American continental snow cover (Groisman *et al.* 1994). Tree ring width and density indices in interior Alaska and high elevation sites in Mongolia indicate that there has been a 2-3°C increase in annual temperatures over the past 100 years, and that temperatures have remained at levels equal to the highest experienced in the last 300-400 years (Jacoby *et al.* 1996; Jacoby *et al.* 1995).

As evidence for climate change becomes less theoretical and more tangible, it is increasingly important to elucidate the carbon balance response of high latitude ecosystems. Keeling *et al.* (1996;1995) measured an increase in the seasonal amplitude of atmospheric CO<sub>2</sub> of 20% at Mauna Loa and 40% at Point Barrow, with drawdown advancing temporally by approximately seven days since 1960. The advance in drawdown and increase in amplitude suggest an advance in the start of the growing season and an increase in vegetation productivity, respectively. Ciais *et al.* (1995) used changes in isotopic carbon concentrations to infer an increase in vegetation productivity at mid to high latitudes of North America. Myneni *et al.* (1997) calculated an increase in vegetation greenness and an advance in the start of the growing season of 8-10 days over the period 1981-1991 using Advanced Very High Resolution Radiometer (AVHRR) measure of the Normalised Difference Vegetation Index (NDVI) in the North American high latitudes.

The results of the above studies all indicate that the high latitudes may be responding as a sink of carbon, but these are not the only studies of ecosystem response to climate change. Both experimental (Billings *et al.* 1982) and observational (Oechel *et al.* 1993) evidence have been collected showing that Arctic tundra systems become net sources of CO<sub>2</sub> to the atmosphere with warmer air temperatures. Field evidence near Barrow, AK also indicates that tundra systems have become net sources of CO<sub>2</sub> over the period 1971-1991 (Oechel *et al.* 1995). With an increase in temperatures large enough to increase

the soil active layer, some boreal forest ecosystems also become net CO<sub>2</sub> sources with decomposition exceeding primary production (Goulden *et al.* 1998).

Reversals in net CO<sub>2</sub> efflux are not the only potential ecosystem feedbacks to climate; boreal forests have a significant albedo feedback affecting surface energy budget, meaning that any change in the areal extent of boreal forest will have a measurable impact on climate. Increases in forest cover result in warmer surface temperatures in winter by reducing the albedo (Bonan *et al.* 1992a). An increase in the areal extent of boreal forest probably accounted for a 4°C spring warming during the Holocene through a reduction in winter albedo (Foley *et al.* 1994). Warmer temperatures may, in addition to increasing potential productivity of existing vegetation, result in an increase in the extent of forests into areas previously unforested. Additional forest cover would reduce the albedo and provide a positive feedback if coincident increases in NPP were not large enough to compensate.

Our objectives in this study are two-fold. First, we aim to quantify any significant trend in long-term surface records of daily climate at the high latitudes of western North America using ecologically sensitive climate variables. Second, we use these long-term daily records to drive an ecosystem process model, BIOME\_BGC (BioGeochemical Cycles) (Hunt *et al.* 1996; Running *et al.* 1988), to examine the effect of interannual variability and long-term climate on the simulated carbon balance of aspen (*Populus tremuloides*) and white spruce (*Picea glauca*) stands.

## Methods

### *Climate Analysis*

We selected meteorological records based on data continuity and completeness. We began with the full Alaskan National Climatic Data Center (NCDC) and Atmospheric Environment Service (AES, of Canada) daily records for northwestern Canada. We extracted sites at latitude greater than 55°N, with record lengths greater than forty years, and that extended through 1997. From this initial subset, we chose all records in which missing observations comprised less than 5% of the entire data set and which had no more than six consecutive months missing in any given year. We obtained ancillary information regarding station history and population growth to ensure data continuity and minimise potential urbanisation effects. We found thirteen stations, 8 in Alaska and 5 in Canada, meeting our selection criteria (Table 1). We replaced missing data using linear interpolation.

Because our objective was to analyse climate with respect to ecosystem function, we seasonalised the climate records according to realised vegetation seasons for the boreal forest zone based on a hydrologic year, October through September (Viereck *et al.* 1993; Van Cleve *et al.* 1991). We defined winter as the 151 day period October through February, spring as the 92 day period March through May, and summer as the 122 day period June through September. We performed least squares regression analysis on ecologically sensitive climate

variables—maximum temperature ( $T_{\max}$ ), minimum temperature ( $T_{\min}$ ), precipitation, and average daily temperature ( $T_{\text{ave}} = [T_{\max} + T_{\min}] / 2$ )—to detect trends through time for averaged daily values in each seasonal subset.

### *Growing Season Length*

We analysed growing season as defined by the phenology submodel of BIOME\_BGC (White *et al.* 1997). The phenology model of White *et al.* (1997) determines yearday of leaf onset and offset using standard surface meteorological data. For temperate latitudes, leaf onset is determined using a combined thermal and radiation summation; for high latitudes a modified thermal summation was developed to account for extremity in sun angles. Leaf offset is a thermally adjusted photoperiod function. We performed least squares regression analysis on the growing season length and the yearday of leaf onset to determine whether a trend was present over the period of record

We analysed an 82 year record of river ice breakup data for interior Alaska as an independent and spatially integrative indicator of springtime surface energy balance. The Tanana River flows through the interior of Alaska and its breakup has been recorded at Nenana, AK every spring since 1917. This record contains the precise time in hours and seconds of ice breakup at the same location on the river through its entirety and can be considered quite reliable (Nenana Ice Classic, tripod@ptialaska.net). Three of our sites, Bettles Field, Fairbanks, and Big Delta, are in the region of the Tanana River. We performed least squares regression on breakup date and correlated it with average spring

temperature and average yearday of leaf onset for these three interior Alaska sites. We calculated the deviation from the long-term mean leaf onset date for each year at each site, averaging the deviations for each year for the three sites, and correlated this mean deviation to yearday of river ice breakup.

### *Simulated Carbon Balance*

We used an ecosystem process model, BIOME\_BGC (recently updated by P.E. Thornton, 1998), to quantify ecosystem response to long-term climate. BIOME\_BGC has been extensively documented (Kimball *et al.* 1997b; Hunt *et al.* 1996; Hunt *et al.* 1992; Running *et al.* 1991; Running *et al.* 1988). BIOME\_BGC requires daily  $T_{\max}$ ,  $T_{\min}$ ,  $T_{\text{ave}}$ , precipitation, vapour pressure deficit (VPD), dewpoint temperature, daylength, and photosynthetically active radiation (PAR). We used a microclimate simulation model, MT-CLIM (Thornton *et al.* 1999; Kimball *et al.* 1997a; Hungerford *et al.* 1989) to compute those variables not present in standard weather station records, correcting for slope, aspect, albedo, and leaf area index. To run MT-CLIM, we initialised each site for flat surface conditions at the same elevation as the original station data.

For the model runs, we parameterised all sites with soil type and depth (Table 2) typical of well-drained upland site conditions in interior Alaska (Van Cleve *et al.* 1983b; Van Cleve *et al.* 1983a; Viereck *et al.* 1983). All physiological variables were also standardised, so that any differences in model output would be due solely to climate. We ran the model for two tree species typical of the boreal forest zone—aspens (broadleaf deciduous) and white spruce (needleleaf

evergreen)—that do not occur with permafrost. We ran the model with an extended spin-up, repeating the full climate dataset, from stand initiation to full canopy stage for each tree species using physiological parameters from the literature (Table 2) (Thornton 1998; Waring *et al.* 1998; Kimball *et al.* 1997; Kozlowski *et al.* 1997; Nobel 1991; Van Cleve *et al.* 1983b; Van Cleve *et al.* 1982; Viereck *et al.* 1983). In order to prevent “tuning” of the model runs, the stand biomass variables output from this spin-up were used to initialize a final, static-allocation, multi-year model run.

In a static-allocation model run, the model is initialized with defined physiological, soil, and vegetation biomass components and forced to grow this equivalent biomass each year. This allocation strategy does not grow a stand of trees; rather, it allows us to simulate the carbon and water balance response of a stand to interannual and long-term climate variability. The benefit of using a static-allocation scheme for this analysis is that it negates any potential affect on ecosystem carbon balance beyond that of climate. We examined tree carbon and water balance output using least squares regression: gross primary production (GPP), maintenance respiration ( $R_m$ ), net primary production (NPP), and evapotranspiration (ET). GPP is the net daily carbon assimilation by photosynthesis minus photorespiration. Maintenance respiration is the total, daily, respired carbon from leaf, stem, and root metabolic processes. Net primary production is GPP minus  $R_m$ , the net daily photosynthetic product available for new growth. ET is daily water loss from surface evaporation and plant transpiration.



Heterotrophic respiration ( $R_h$ ) is another significant component of ecosystem carbon balance. In BIOME\_BGC,  $R_h$  is computed by first determining a climate dependent decomposition rate scalar (DRS) and multiplying this by litter and soil carbon pools, each with substrate specific decomposition rates. The decomposition rate scalar (DRS) for BIOME\_BGC soil and litter pools is the product of a temperature dependent rate scalar and a soil water dependent rate scalar and is the component of  $R_h$  that responds directly to climate variability. Once calculated, this DRS is used to determine the rate of decomposition for individual organic matter pools. The nature of a static-allocation model run also does not lend itself to an analysis of absolute heterotrophic respiration as calculation of actual  $R_h$  requires dynamic soil and litter pools. We can, though, examine the effect of climate variability on the rate of decomposition processes. To determine heterotrophic process response to climate, we output the mean DRS for each year and performed least squares regression.

## **Results and Discussion**

### *Climate Analysis*

All significant trends in temperature variables were positive; no consistent trend was present in precipitation data (not presented). Annual average temperature increased for all sites an average of 0.31 °C/10yrs (Table 1). Regionally, we found a general pattern of larger temperature increases in the Alaskan station records than in the Canadian station records.

Temperature extrema had the greatest magnitude of change in the spring months, March through May, followed in magnitude by winter and summer; minimum temperature trends were greater overall than maximum (Table 3a, b). Winter  $T_{\min}$  increased an average of  $0.35^{\circ}\text{C}/10\text{yrs}$  and  $T_{\max}$  an average of  $0.24^{\circ}\text{C}/10\text{yrs}$ ; summer  $T_{\min}$  increased an average of  $0.23^{\circ}\text{C}/10\text{yrs}$  and  $T_{\max}$  an average  $0.14^{\circ}\text{C}/10\text{yrs}$ . Spring  $T_{\min}$  increased an average of  $0.47^{\circ}\text{C}/10\text{yrs}$ , with increases greater in magnitude and significance (all  $p < 0.05$ ) for the Alaskan stations than for Canadian stations. Spring  $T_{\max}$  increases averaged  $0.46^{\circ}\text{C}/10\text{yrs}$ , with less difference between the Alaskan and Canadian stations. These increases in spring temperature are especially important from an ecological perspective because of the potential affect on the timing of spring thaw and initiation of growing season.

The breakup of river ice integrates a regional energy budget and is also highly correlated with spring temperatures making it an excellent non-point specific climate gauge. The long-term mean ice breakup date for the Tanana River at Nenana, AK, is yearday 125, or 5 May. Spring breakup on the Tanana River has advanced by  $0.71\text{ days}/10\text{yrs}$  ( $p = 0.01$ ) coincident with increases in spring surface temperature in interior Alaska (Fig. 1). In addition to advancing ice breakup, increases in spring temperatures stimulate an earlier melting of the snowpack (Groisman *et al.* 1994). At high latitudes, the freeze/thaw transition is a period of active energy and carbon exchange between the atmosphere and

biosphere. An earlier transition will stimulate an earlier commencement of microbial activity in the soils and start of photosynthesis in evergreen plants.

#### *Growing season length*

The growing season has lengthened by an average of 2.66 days/10yrs (Table 4). As the regional patterns in temperature increases would indicate, increases in growing season length were generally greater in magnitude for the stations in Alaska versus those in Canada; a general increase in magnitude occurs with decrease in latitude. Only two Canadian stations, Fort McMurray and Fort St. John, have increases in growing season length on the order of magnitude of the Alaskan stations, 2.26 and 2.04 days/10yrs, respectively (Table 4).

Although the absolute magnitude of increase in active growing season length is variable among the sites, a consistent increase is present in this dataset. The increases in growing season length occur with an advance in the timing of leaf onset in the spring of 1.10 days/10yrs (Figure 2). The average yearday of leaf onset for the three interior Alaska sites had a positive correlation with Tanana River breakup for the period 1949-1997 ( $r^2=0.85$ ,  $p<0.0001$ ). Modeled leaf onset for Fairbanks correlates positively ( $r^2=0.84$ ,  $p \leq 0.01$ ) with observed aspen phenology greenup for Fairbanks for the period 1974-1997 (James Anderson, *personal communication*, 1999). Inferences of advances in growing season from AVHRR (Myneni *et al.* 1997) and atmospheric CO<sub>2</sub> sources (Keeling *et al.* 1996; Ciais *et al.* 1995) are consistent with these surface

measures of temperature, river breakup date, and modelled phenology indicating that there has been a measurable advance in and lengthening of the growing season.

### *Simulated Carbon Balance*

Increases in growing season length will not necessarily result in an increase in net ecosystem productivity (NEP) at high latitudes. NEP is the balance between net primary productivity (NPP) and heterotrophic respiration ( $R_h$ ). All significant changes in both GPP and NPP were positive for aspen and spruce stands. The average increase in spruce GPP was  $0.02 \text{ kgC/m}^2/10\text{yrs}$  (12%) and in Aspen was  $0.03 \text{ kgC/m}^2/10\text{yrs}$  (14%). Deciduous trees have higher maximum potential stomatal conductance (Table 2) and potential assimilation rate ( $A_{\text{max}}$ ) than evergreen trees (Waring *et al.* 1998; Kozlowski *et al.* 1997). Biochemically, aspen also has a higher optimum temperature for photosynthesis than spruce (Table 2), but it is not likely that this explains the greater increases in GPP for aspen sites. Temperature increases were greater in spring than summer and we can assume that the longer growing season and greater potential  $A_{\text{max}}$  are responsible for greater GPP increases in aspen.

Maintenance respiration ( $R_m$ ) increased throughout the data set; aspen increases averaged  $4.2 \times 10^{-3} \text{ kgC/m}^2/10\text{yrs}$  (15%) and spruce increases averaged  $5.20 \times 10^{-3} \text{ kgC/m}^2/10\text{yrs}$  (10%). Aspen stands had 50% greater response to climate changes than did spruce. Maintenance respiration increases exponentially with temperature and is sensitive to tissue nitrogen content

(Waring *et al.* 1998; Ryan 1991). The greater per cent nitrogen in aspen, 2%, vs. spruce, 1%, leaves explains this increased sensitivity (Ryan 1991; Van Cleve *et al.* 1983b). Both aspen and spruce have an average 20% increase in NPP. Aspen NPP increased by  $0.02 \text{ kgC/m}^2/10\text{yrs}$  and spruce NPP increased  $0.01 \text{ kgC/m}^2/10\text{yrs}$  (Figure 3). The 50% greater response of aspen  $R_m$  relative to GPP response to warming accounts for the equivalence in NPP per cent change for the two species. NPP is the net carbon balance term for the tree and is controlled indirectly by the individual controls on GPP and  $R_m$ .

At the coldest of the interior sites, Bettles Field, AK, annual NPP ranges from  $0.30\text{--}0.50 \text{ kgC/m}^2/\text{yr}$  (Fig. 3a) and corresponds closely to the magnitude of growing season length. Net primary production for spruce ranges from  $0.20\text{--}0.40 \text{ kgC/m}^2/\text{yr}$  (Fig. 3c) and corresponds more closely with precipitation patterns; low NPP years occur in or immediately after years of low annual precipitation input. The effect of a long (18 days longer than the long term mean (LTM)) and dry (lowest annual precipitation on record) growing season on NPP is evident in 1969 for both species. The effect of growing season length on NPP is also evident in 1992, after the Mount Pinatubo eruption of 1991. The growing season is 25 days longer than the LTM in 1991 and 26 days shorter in 1992, and both species experience a drop in NPP in 1992. This 'Pinatubo effect' is present in all of the interior Alaska records.

At the warmest of the interior sites, Fort McMurray, aspen NPP ranges from ca.  $0.70\text{--}1.00 \text{ kgC/m}^2/\text{yr}$  (Fig. 3b). Years of exceptionally low NPP are a result of low GPP and correspond to years with a combination of short growing

season and low precipitation. Spruce NPP ranges from 0.25-0.45 kgC/m<sup>2</sup>/yr (Fig. 3d). There is a consistent increase in modeled NPP for spruce at Fort McMurray, paralleling temperature more than precipitation. The differences in magnitude and interannual variability for aspen and spruce between these two sites reflect the range of site-specific effects on carbon balance across the dataset.

For all sites, both the magnitude and range of NPP are within bounds of measured above-ground productivity for aspen and spruce in Alaska (Van Cleve *et al.* 1983b; Yarie *et al.* 1983). With dynamic response of the vegetation to climate the relative increases in NPP for the two species may not remain equal. The evapotranspirational demand of spruce canopies increased an average of 15.3% over the period of record compared to an 8.3% increase for aspen canopies. Without increases in precipitation, the increases in temperature and ET may limit spruce NPP over time. Jacoby *et al.* (1995) found evidence of a lack of increased growth in white spruce in Alaska although tree ring chronologies indicated warmer growing season temperatures, and postulated that this is due to water stress.

The other half of the ecosystem carbon balance equation is that of carbon efflux due to decomposition processes in the litter and soil. The mean increase in the decomposition rate scalar (DRS) was 17.3% for aspen and 16% for spruce (Fig. 4). As with the GPP and NPP, the per cent increase was larger at Ft. McMurray (42%) than at Bettles Field (26%). To some degree, the trajectories of modeled NPP and decomposition rate parallel one another, as both rely on

adequate temperature and moisture conditions. As the average ET rate was higher for spruce than aspen, on average and specifically for these sites, the smaller increase in decomposition on spruce sites is expected. A decrease in soil water availability due to increases in or high rates of ET will suppress increases in rate scalar from temperature alone. Incorporating the substrate quality into calculation of  $R_h$  will further affect the net result. The differences in substrate quality between aspen and spruce litter will amplify the differences in DRS and net carbon flux from the soil.

As the taiga is underlain by discontinuous permafrost, decomposition is limited to the active layer and much organic matter remains frozen year round. Permafrost presence requires an annual average temperature of  $-1\text{ }^{\circ}\text{C}$  (Van Cleve *et al.* 1983b; Kane *et al.* 1991). At four of the interior sites—Fairbanks and Bettles Field, AK, Ft. Nelson, BC and Hay River, NWT—the increases in annual average temperature are greater than  $2\text{ }^{\circ}\text{C}$  (Table 1) raising annual averages to near  $0\text{ }^{\circ}\text{C}$ , the thermal boundary for permafrost. The active layer has likely already increased across much of the North American high latitudes, decreasing the distribution of permafrost and making previously unavailable organic matter available to decomposition, likely enhancing the net efflux from soils.

It is important when considering the effects of climate change on carbon balance to consider the vegetation distribution of the taiga. The site types that we have simulated are an important, but limited, component of the landscape both successional and geographically. With respect to soil carbon pools and

potential for increased decomposition and efflux with warming, both white and black spruce (*Picea mariana*) forest stands have the greatest potential for feedback due to large stores of soil organic matter. Black spruce occurs with permafrost on flat and north facing aspects. The aspect of black spruce sites will result in a smaller increase in temperatures relative to stands on southern aspects, but the potential changes in active layer thickness and decomposition rates remain relevant. If melting of permafrost occurs, increasing the active layer will increase decomposition as previously frozen organic matter is exposed. As black spruce stands have very low rates of productivity and slow growth, warming of these sites will likely result in net efflux of carbon to the atmosphere if decomposition exceeds primary production (Goulden *et al.* 1998).

The differences in response to climate change between the aspen and spruce stands may have important successional and carbon balance consequences. In upland habitat types of the taiga, aspen is an early post-disturbance dominant species. The increases in decomposition rate and NPP on aspen site types, when taken with the labile nature of deciduous litter, could inhibit succession to white spruce through slower accumulation of organic matter and subsequent soil cooling. An increase in fire frequency or other disturbance with warmer drier conditions may also maintain aspen dominance. Warmer temperatures may keep these sites in more productive deciduous stages for a longer period of time.



## Conclusions

Analysis of long-term daily surface temperature records quantified the magnitude and regional pattern of climate change at high latitudes. All significant changes in both climate and modelled carbon balance variables were positive. Increases in growing season length provide surface-measured collaboration to inferences of the same from satellite, atmospheric CO<sub>2</sub>, and sea surface temperature sources (Myneni *et al.* 1997; Keeling *et al.* 1996; Chapman *et al.* 1993). The increases in surface temperature extrema are consistent with regional warming trends observed in larger spatial data sets (Hammond *et al.* 1996; Serreze *et al.* in press). The climate of the high latitudes has changed significantly in this century with important consequences for both high latitude ecosystems and atmospheric CO<sub>2</sub> concentrations.

We have calculated a positive carbon balance response for mature productive forest stands to observed climate changes. The climate-controlled rate of decomposition has also increased, but the absolute magnitude of carbon flux will be species specific according to the biochemistry of broadleaf vs. needleleaf litter decomposition. Our results do not indicate a major shift in net carbon flux from productive forest stands. Much evidence, though, indicates that there may be a significant carbon flux response to climate induced increases in active layer depth in permafrost dominated forest and tundra ecosystems (Goulden *et al.* 1998; Oechel *et al.* 1995; Oechel *et al.* 1994; Oechel *et al.* 1993; Billings *et al.* 1982).

The zone of discontinuous permafrost will be strongly affected by changes in climate, and it is possible that the carbon balance changes in this region will be the key to determining net high latitude response to climate change. A spatially integrated regional simulation is needed to include the dynamics of topography, microclimate and species distribution in calculating net carbon flux changes. This is hindered by difficulties in accurately initialising soil organic matter and vegetation biomass, and modelling the dynamics of the freeze/thaw transition at the regional scale. Recent advances have been made in tracking and mapping freeze/thaw dynamics at the high latitudes using radar (Running *et al.* 1999; Way *et al.* 1997) and scatterometer (McDonald *et al.* 1998). These techniques provide high resolution mapping of the state of water in the landscape—in soils and vegetation—and would integrate well into regional simulations. With advances in remote measurement of system dynamics such as this, we are making progress in overcoming our limitations to capturing the ecosystem dynamics of this region.

## References

- Billings WD, Luken JO, Mortensen DA, Peterson KM (1982) Arctic Tundra: A Source or Sink for Atmospheric Carbon Dioxide in a Changing Environment? *Oecologia*, **53**, 7-11.
- Bonan GB, Pollard D, Thompson SL (1992a) Effects of boreal forest vegetation on global climate. *Nature*, **359**, 716-718.
- Bonan GB, Shugart HH (1989) Environmental factors and ecological processes in boreal forests. *Annual Review of Ecology and Systematics*, **20**, 1-28.
- Bonan GB, Van Cleve K (1992b) Soil temperature, nitrogen mineralization, and carbon source-sink relationships in boreal forests. *Canadian Journal of Forest Research*, **22**, 629-639.
- Chapman WL, Walsh JE (1993) Recent variations of sea ice and air temperature in high latitudes. *Bulletin of American Meteorological Society*, **74**, 33-47.
- Ciais P, Tans PP, Trolier M, White JWC, Francey RJ (1995) A large northern hemisphere terrestrial CO<sub>2</sub> sink indicated by the <sup>13</sup>C/<sup>12</sup>C ratio of atmospheric CO<sub>2</sub>. *Science*, **269**, 1098-1102.
- Foley JA, Kutzbach JE, Coe MT, Levis S (1994) Feedbacks between climate and boreal forests during the Holocene epoch. *Nature*, **371**, 52-54.
- Gates DM (1993) *Plant-Atmosphere Relationships*, Chapman and Hall, New York, 92 pp.
- Goulden ML, Wofsy SC, Harden JW, *et al.* (1998) Sensitivity of boreal forest carbon balance to soil thaw. *Science*, **279**, 214-216.
- Groisman PY, Karl TR, Knight RW (1994) Observed impact of snow cover on the heat balance and the rise of continental spring temperatures. *Science*, **263**, 198-200.
- Hammond T, Yarie J (1996) Spatial prediction of climatic state factor regions in Alaska. *Ecoscience*, **3**, 490-501.
- Hungerford RD, Nemani RR, Running SW, Coughlan JC (1989) MT-CLIM: A Mountain Microclimate Simulation Model, USDA Forest Service Intermountain Research Station, *Research Paper INT-414*, Ogden, UT, 52 pp.

- Hunt ER, Jr., Piper SC, Nemani R, Keeling CD, Otto RD, Running SW (1996) Global net carbon exchange and intra-annual atmospheric CO<sub>2</sub> concentrations predicted by an ecosystem process model and three-dimensional atmospheric transport model. *Global Biogeochemical Cycles*, **10**, 431-456.
- Hunt ER, Jr., Running SW (1992) Simulated dry matter yields for aspen and spruce stands in the North American boreal forest. *Canadian Journal of Remote Sensing*, **18**, 126-133.
- IPCC (1995) *Climate Change 1995: The Science of Climate Change*. Cambridge University Press, Cambridge.
- Jacoby GC, D'Arrigo RD (1995) Tree ring width and density evidence of climatic and potential forest change in Alaska. *Global Biogeochemical Cycles*, **9**, 227-234.
- Jacoby GC, D'Arrigo RD, Davaajamts T (1996) Mongolian tree rings and 20th-century warming. *Science*, **273**, 771-773.
- Kane DL, Hinzman LD, Zarling JP (1991) Thermal response of the active layer to climatic warming in a permafrost environment. *Cold Regions Science and Technology*, **19**, 111-122.
- Keeling CD, Chin JFS, Whorf TP (1996) Increased activity of northern vegetation inferred from atmospheric CO<sub>2</sub> measurements. *Nature*, **382**, 146-149.
- Keeling CD, Whorf TP, Wahlen M, van der Plicht J (1995) Interannual extremes in the rate of rise of atmospheric carbon dioxide since 1980. *Nature*, **375**, 666-670.
- Kimball JS, Running SW, Nemani R (1997a) An improved method for estimating surface humidity from daily minimum temperature. *Agricultural and Forest Meteorology*, **85**, 87-98.
- Kimball JS, Thornton PE, White MA, Running SW (1997b) Simulating forest productivity and surface-atmosphere carbon exchange in the BOREAS study region. *Tree Physiology*, **17**, 589-599.
- Kozlowski TT, Pallardy SG (1997) *Physiology of Woody Plants*, Academic Press, San Diego, 411pp.
- McDonald KC, Kimball JS, Zimmermann R, Way JB, Running SW, Frohking S (1998) In *1998 Fall Meeting of the American Geophysical Union*. American Geophysical Union, San Francisco.

- Myneni RB, Keeling CD, Tucker CJ, Asrar G, Nemani RR (1997) Increased plant growth in the northern high latitudes from 1981 to 1991. *Nature*, **386**, 698-702.
- Nobel PS (1991) *Physicochemical and Environmental Plant Physiology*, Academic Press, San Diego, 635 pp.
- Oechel WC, Cowles S, Grulke N, et al. (1994) Transient nature of CO<sub>2</sub> fertilization in arctic tundra. *Nature*, **371**, 500-503.
- Oechel WC, Hastings SJ, Vourlitis G, Jenkins M, Riechers G, Grulke N (1993) Recent change of Arctic tundra ecosystems from a net carbon dioxide sink to a source. *Nature*, **361**, 520-523.
- Oechel WC, Vourlitis GL, Hastings SJ, Bochkarev SA (1995) Change in arctic CO<sub>2</sub> flux over two decades: effects of climate change at Barrow, Alaska. *Ecological Applications*, **5**, 846-855.
- Running SW, Coughlan JC (1988) A general model of forest ecosystem processes for regional applications I. Hydrologic balance, canopy gas exchange and primary production processes. *Ecological Modelling*, **42**, 125-154.
- Running SW, Gower ST (1991) FOREST-BGC, A general model of forest ecosystem processes for regional applications. II. Dynamic carbon allocation and nitrogen budgets. *Tree Physiology*, **9**, 147-160.
- Running SW, Way JB, McDonald KC, Kimball JS, Frolking S, Keyser AR, Zimmermann R (1999) Radar Remote Sensing Proposed for Monitoring Freeze-Thaw Transitions in Boreal Regions. *Eos*, **80**, 213, 220-221.
- Ryan MG (1991) Effects of climate change on plant respiration. *Ecological Applications*, **1**, 157-167.
- Serreze MC, Walsh JE, FS Chapin III., et al. (in press) Observational evidence of recent change in the northern high-latitude environment. *Climatic Change*.
- Thornton PE (1998) *Regional Ecosystem Simulation: Combining Surface- and Satellite-Based Observations to Study Linkages between Terrestrial Energy and Mass Budgets*. PhD Thesis, University of Montana, Missoula, pp. 280.

- Thornton PE, Running SW (1999) An improved algorithm for estimating incident daily solar radiation from measurements of temperature, humidity, and precipitation. *Agricultural and Forest Meteorology*, **93**, 211-228.
- Van Cleve K, FS Chapin III., Dyrness CT, Viereck LA (1991) Element cycling in taiga forests: State-factor control. *BioScience*, **41**, 78-88.
- Van Cleve K, Dyrness CT, Viereck LA, Fox J, FS Chapin III, Oechel W (1983a) Taiga ecosystems in interior Alaska. *BioScience*, **33**, 39-44.
- Van Cleve K, Oliver L, Schlentner R, Viereck LA, Dyrness CT (1983b) Productivity and nutrient cycling in taiga forest ecosystems. *Canadian Journal of Forest Research*, **13**, 747-766.
- Van Cleve K, Oliver LK (1982) Growth response of postfire quaking aspen (*Populus tremuloides* Michx.) to N, P, and K fertilization. *Canadian Journal of Forest Research*, **12**, 160-165.
- Viereck LA, Dyrness CT, Van Cleve K, Foote MJ (1983) Vegetation, soils, and forest productivity in selected forest types in interior Alaska. *Canadian Journal of Forest Research*, **13**, 703-720.
- Viereck LA, Van Cleve K, Adams PC, Schlentner RE (1993) Climate on the Tanana River floodplain near Fairbanks, Alaska. *Canadian Journal of Forest Research*, **23**, 899-913.
- Waring RH, Running SW (1998) *Forest Ecosystems Analysis at Multiple Scales*, Academic Press, San Diego, 370 pp.
- Way J, Zimmermann R, Rignot E, McDonald K, Oren R (1997) Winter and spring thaw as observed with imaging radar at BOREAS. *Journal of Geophysical Research*, **102**, 29,673-629,684.
- White MA, Thornton PE, Running SW (1997) A continental phenology model for monitoring vegetation responses to interannual climatic variability. *Global Biogeochemical Cycles*, **11**, 217-234.
- Yarie J, Van Cleve K (1983) Biomass and productivity of white spruce stands in interior Alaska. *Canadian Journal of Forest Research*, **13**, 767-772.

**Table 1.** Station descriptions. Meteorological station location coordinates, elevation, first year of record (all records end in 1997), and annual average temperature statistics (long-term means and trends).

Site	Latitude	Longitude	Elevation (m)	Start year	Average temp. (°C)	Average temp. Change (°C/10yrs)
<i>Alaska</i>						
Barrow	71.30	-156.79	9.45	1949	-12.3 (1.2)	0.22 (0.1)
Bettles Field	66.92	-151.52	196.34	1952	-5.5 (1.3)	0.45 (0.1)**
Fairbanks	64.82	-147.87	132.93	1949	-2.9 (1.3)	0.42 (0.1)**
Big Delta	64.00	-145.73	386.59	1949	-2.2 (1.4)	0.34 (0.1)*
Anchorage	61.17	-150.02	34.76	1954	2.2 (1.2)	0.27 (0.1)*
Talkeetna	62.30	-150.10	105.18	1949	0.7 (1.2)	0.40 (0.1)**
Yakutat	59.52	-139.67	8.54	1949	4.0 (1.1)	0.20 (0.1)*
Juneau	58.37	-134.68	3.66	1950	4.8 (1.0)	0.13 (0.1)
<i>Canada</i>						
Yellowknife	62.47	-114.45	205.00	1942	-5.1 (1.1)	0.41 (0.1)*
Hay River	60.83	-115.78	166.00	1944	-3.3 (1.1)	0.42 (0.1)**
Ft. Nelson	58.83	-122.58	382.00	1938	-1.0 (1.1)	0.22 (0.1)*
Ft. McMurray	56.65	-111.22	369.00	1944	0.2 (1.2)	0.38 (0.1)**
Ft. St. John	56.23	-120.73	695.00	1942	1.7 (1.2)	0.19 (0.1)

SE for temperature data are reported in parentheses.

\*  $p < 0.05$ ; \*\*  $p < 0.001$

**Table 2.** BIOME\_BGC physiological and soil parameters for simulation runs.

	ASPEN	SPRUCE
LAI (projected)	1.5	2.4
Per cent sand by volume in rock-free soil	30	30
Per cent silt by volume in rock-free soil	55	55
Per cent clay by volume in rock-free soil	15	15
Maximum leaf stomatal conductance, mm/s	5.0	3.0
Maximum leaf boundary layer conductance, mm/s	0.8	50
Optimal temperature for $g_c$ , °C	25	20
Maximum temperature for $g_c$ , °C	40	40
PSI at start of $g_c$ reduction, MPa	-0.5	-0.5
PSI at completion of $g_c$ reduction, MPa	-2.3	-2.0
VPD at start of $g_c$ reduction, kPa	1000	750
VPD at end of $g_c$ reduction, kPa	4000	2000
Effective soil depth, m	0.8	0.8
Site short wave albedo (snow free)	0.2	0.2

LAI, leaf area index;  $g_c$ , canopy conductance to water vapor; PSI, soil water potential; VPD, vapor pressure deficit.



**Table 3a.** Summary of trends in seasonal values for maximum daily temperature. The change and SE are given per decade ( $^{\circ}\text{C}$  per 10y).

Site	Winter			Spring			Summer		
	Change	SE	<i>p</i>	Change	SE	<i>p</i>	Change	SE	<i>p</i>
<i>Alaska</i>									
Barrow	.068	0.2	0.753	0.36	0.2	0.047	0.27	0.1	0.049
Bettles Field	0.37	0.3	0.149	0.69	0.2	0.004	0.21	0.1	0.057
Fairbanks	0.38	0.2	0.115	0.59	0.2	0.010	0.19	0.1	0.063
Big Delta	0.41	0.2	0.095	0.69	0.2	0.005	0.19	0.1	0.014
Anchorage	0.30	0.2	0.165	0.46	0.2	0.026	0.16	0.1	0.134
Talkeetna	0.35	0.2	0.060	0.32	0.2	0.062	0.11	0.1	0.273
Yakutat	0.19	0.2	0.199	0.50	0.1	0.001	0.22	0.1	0.014
Juneau	0.32	0.2	0.044	0.46	0.1	0.000	0.09	0.1	0.339
<i>Canada</i>									
Yellowknife	0.05	0.2	0.773	0.40	0.2	0.008	0.14	0.1	0.091
Hay River	0.20	0.2	0.356	0.43	0.2	0.031	0.22	0.1	0.024
Fort Nelson	0.13	0.2	0.429	0.25	0.1	0.074	-4.0E-03	0.1	0.950
Fort McMurray	0.15	0.2	0.460	0.56	0.2	0.001	0.10	0.1	0.232
Fort St. John	0.23	0.2	0.305	0.31	0.1	0.030	-0.07	0.1	0.397

**Table 3b.** Summary of trends in seasonal values for daily minimum temperature. The change and SE are given per decade ( $^{\circ}\text{C}$  per 10y).

Site	Winter			Spring			Summer		
	Change	SE	<i>p</i>	Change	SE	<i>p</i>	Change	SE	<i>p</i>
<i>Alaska</i>									
Barrow	0.08	0.2	0.714	0.38	0.3	0.025	0.07	0.1	0.501
Bettles Field	0.42	0.3	0.135	0.70	0.3	0.008	0.31	0.1	0.002
Fairbanks	0.53	0.2	0.029	0.64	0.2	0.004	0.40	0.1	0.000
Big Delta	0.34	0.3	0.230	0.44	0.2	0.050	0.10	0.1	0.194
Anchorage	0.68	0.3	0.013	0.58	0.2	0.006	0.27	0.1	0.002
Talkeetna	0.74	0.3	0.005	0.65	0.2	0.000	0.30	0.1	0.000
Yakutat	0.30	0.2	0.200	0.40	0.1	0.007	0.12	0.1	0.129
Juneau	0.57	0.2	0.015	0.58	0.1	0.000	0.48	0.1	0.000
<i>Canada</i>									
Yellowknife	0.10	0.2	0.574	0.33	0.2	0.066	0.21	0.1	0.006
Hay River	0.17	0.2	0.430	0.29	0.2	0.125	0.08	0.1	0.210
Fort Nelson	0.04	0.2	0.799	0.18	0.1	0.173	0.09	0.04	0.053
Fort McMurray	0.37	0.2	0.101	0.65	0.2	0.000	0.46	0.1	0.000
Fort St. John	0.23	0.2	0.322	0.33	0.1	0.023	0.09	0.1	0.083

**Table 4.** Summary of trends in growing season length ( $\pm 1$ SE), yearday leaf offset minus yearday leaf onset, as defined by the phenology sub-model of BIOME\_BGC (days per 10y).

Site	Change	<i>p</i>
<i>Alaska</i>		
Barrow*	1.87 (1.14)	0.109
Bettles Field	2.29 (1.19)	<0.10
Fairbanks	2.54 (1.03)	<0.05
Big Delta	2.46 (1.09)	<0.05
Anchorage	2.62 (1.30)	<0.05
Talkeetna	1.51 (0.92)	<0.15
Yakutat	6.97 (1.71)	<0.001
Juneau	6.54 (1.36)	<0.001
<i>Canada</i>		
Yellowknife	0.71 (0.97)	>0.25
Hay River	0.48 (0.99)	>0.25
Ft. Nelson	1.30 (0.81)	<0.15
Ft. McMurray	2.26 (0.89)	<0.05
Ft. St. John	2.05 (0.87)	<0.05

\* Values for Barrow are calculated using a temperature proxy of 5°C to calculate number of growing season days.

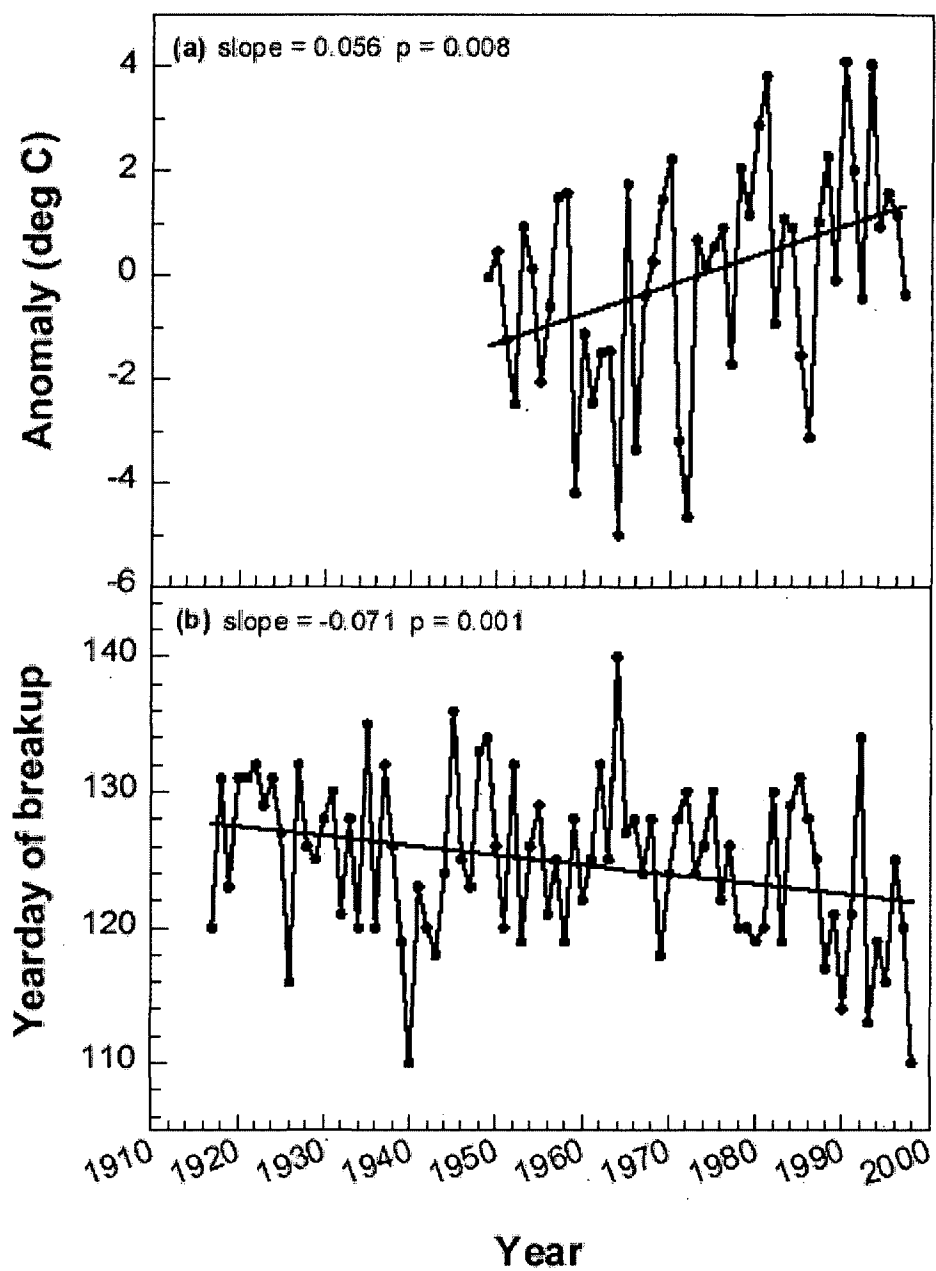


Figure 1.

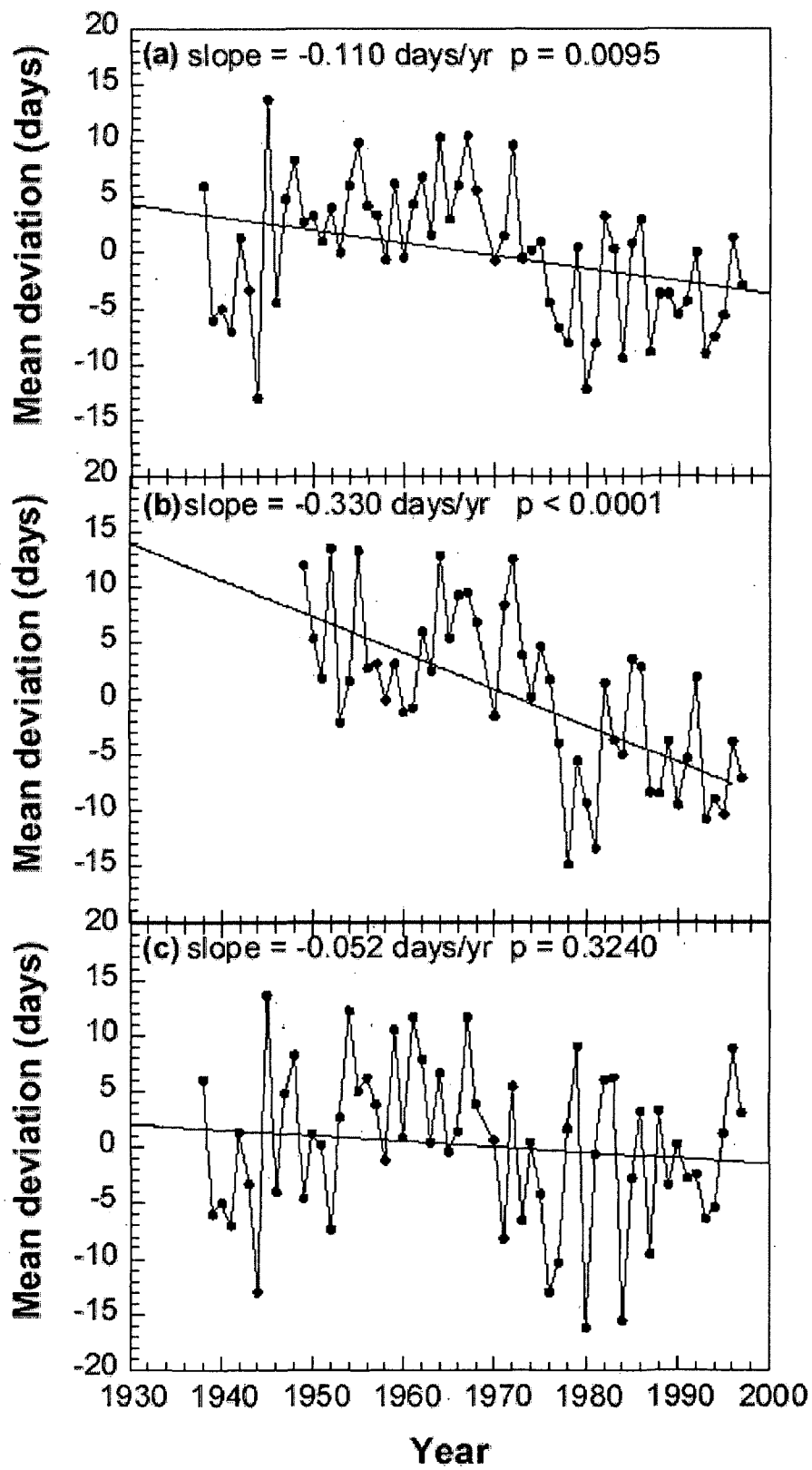


Figure 2.

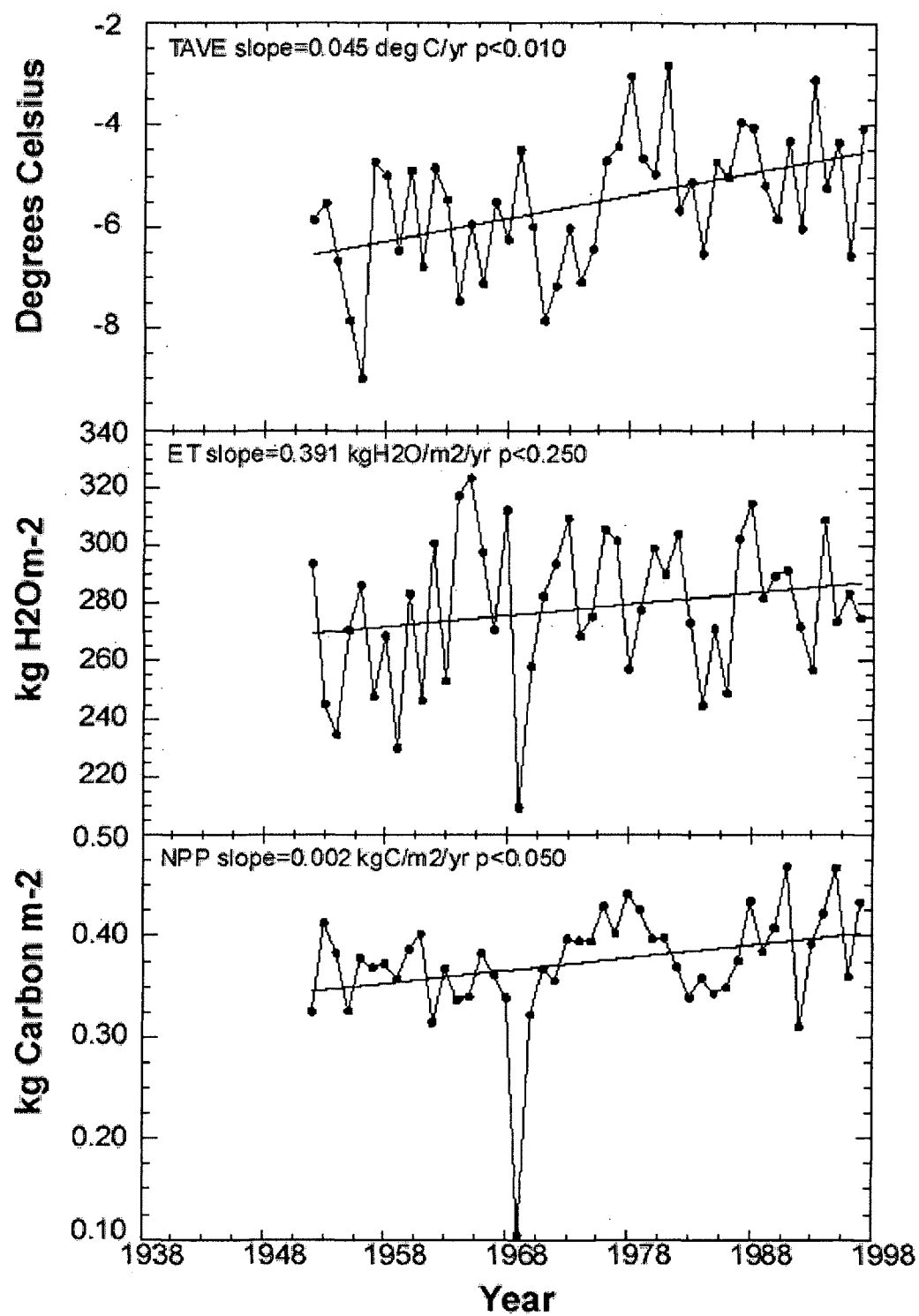


Figure 3a. Aspen @ Bettles Field, AK.

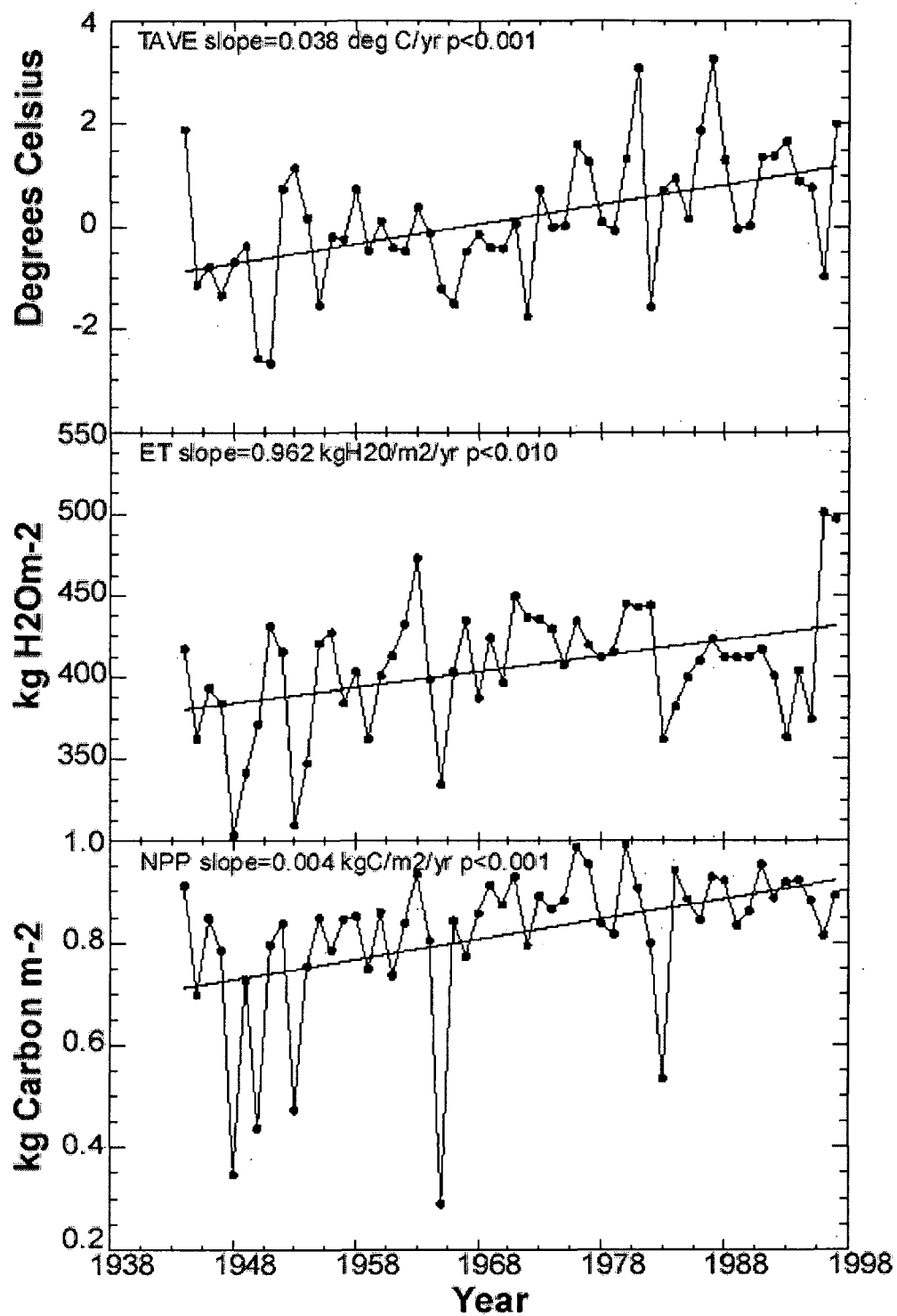


Figure 3b. Aspen @ Ft. McMurray.

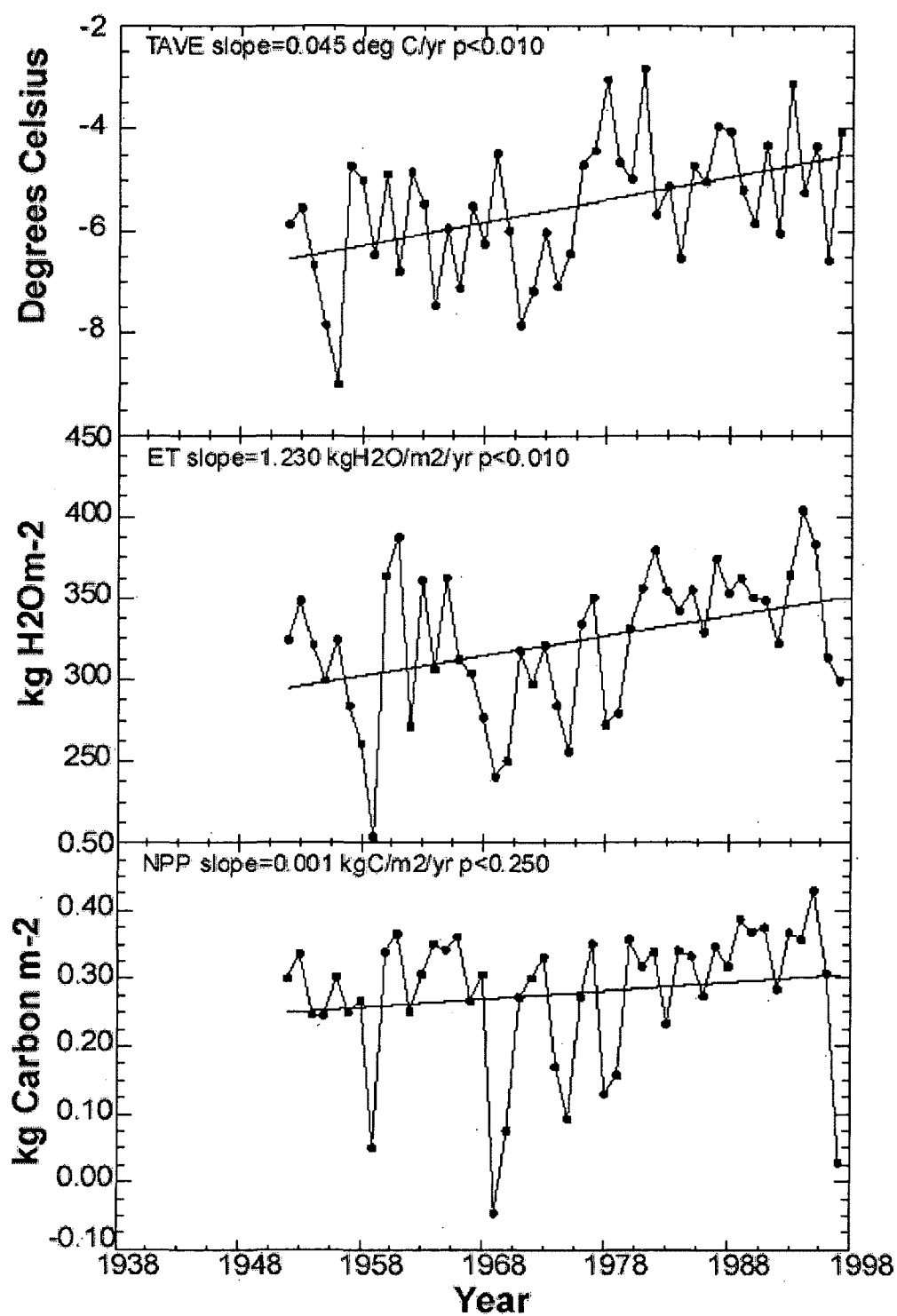


Figure 3c. White spruce at Bettles Field, AK.



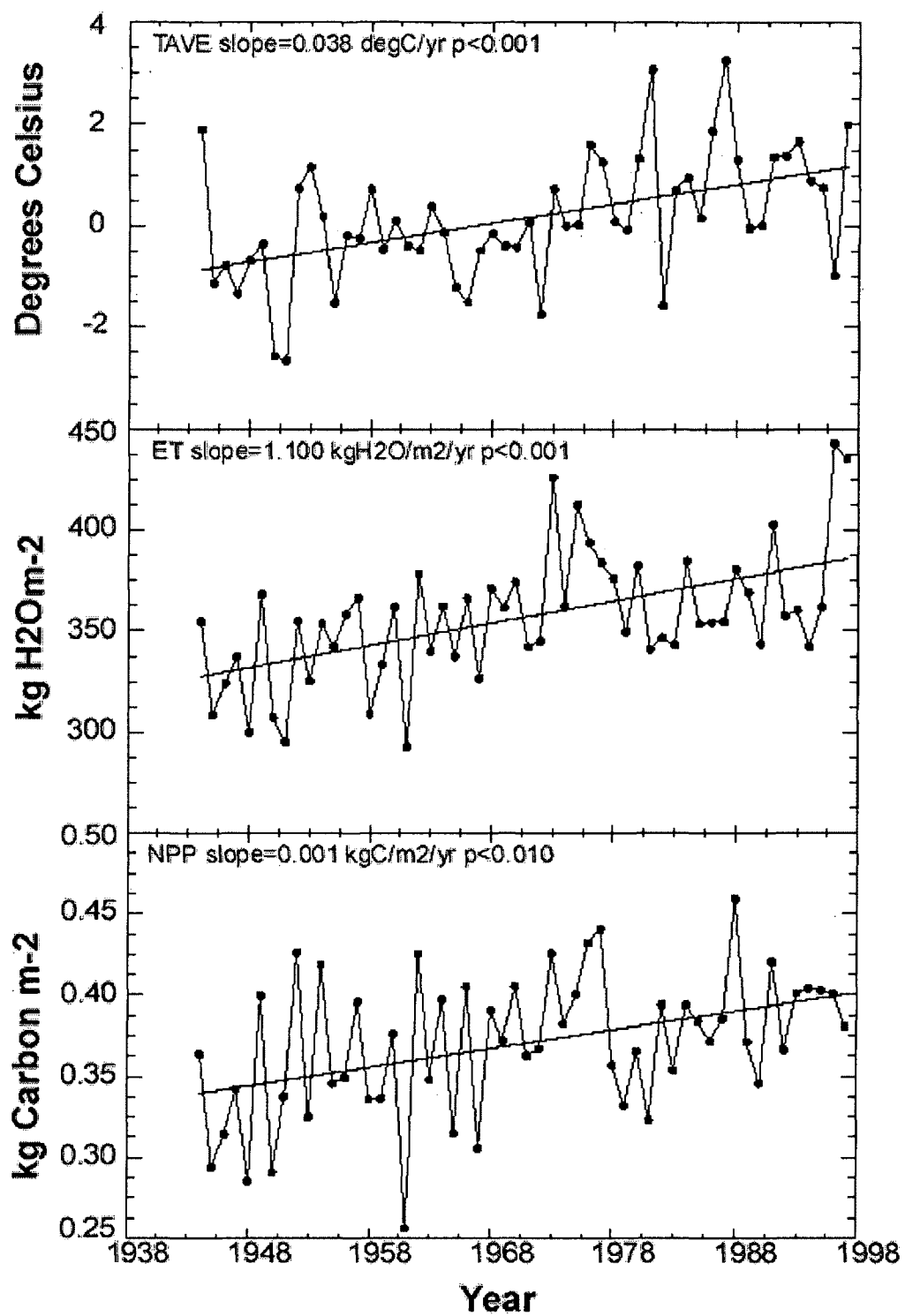


Figure 3d. White spruce @ Ft. McMurray.

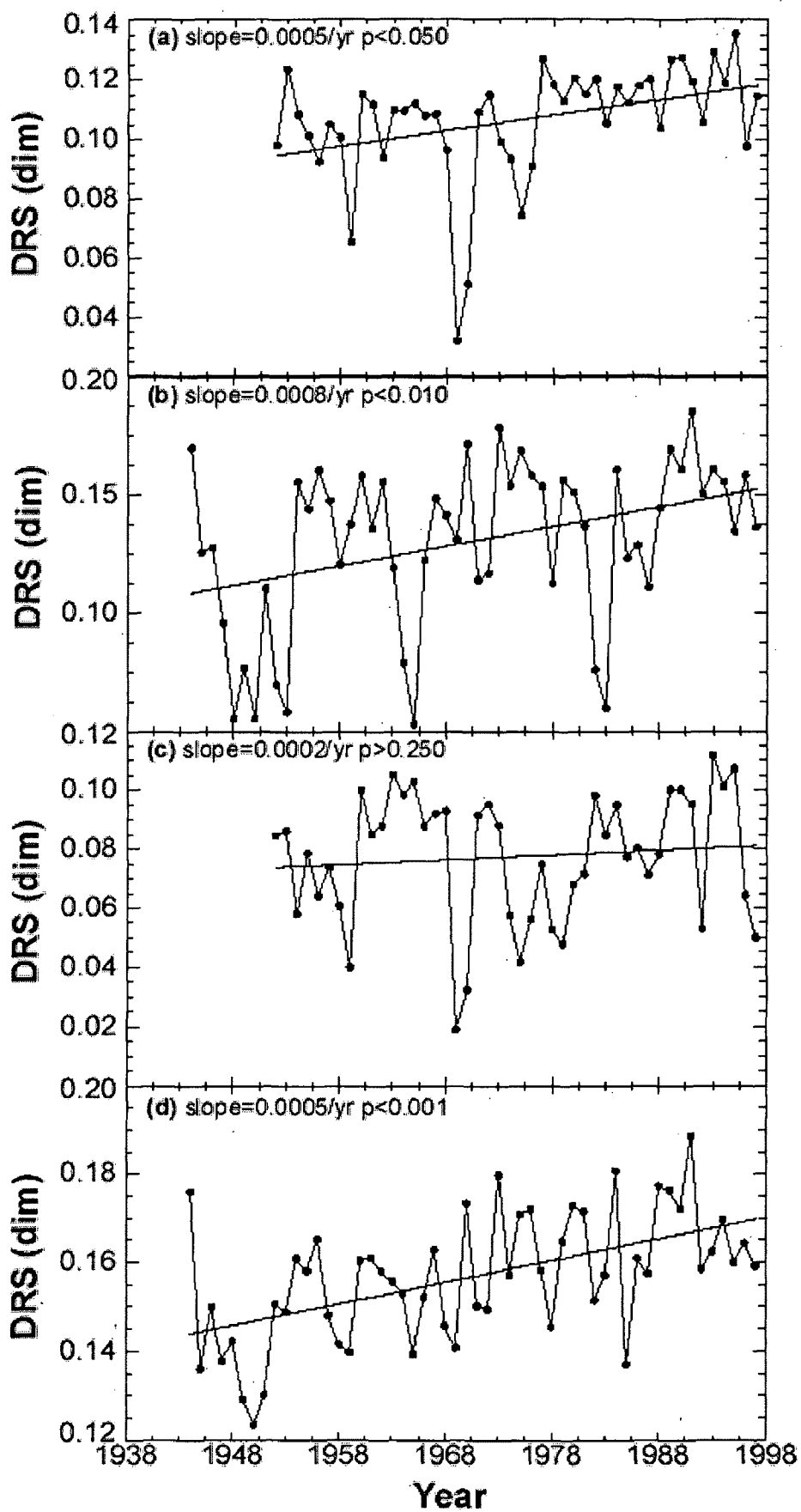


Figure 4.